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Numerical experiments on the probability of seepage into underground openings in heterogeneous fractured rock

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Abstract

An important issue for the performance of underground nuclear waste repositories is the rate of seepage into the waste emplacement drifts. A prediction of this rate is particularly complicated for the potential repository site at Yucca Mountain, Nevada, because it is located in thick, unsaturated, fractured tuff formations. Underground openings in unsaturated media might act as capillary barriers, diverting water around them. In the present work, we study the potential rate of seepage into drifts as a function of the percolation flux at Yucca Mountain, based on a stochastic model of the fractured rock mass in the drift vicinity. A variety of flow scenarios are considered, assuming present-day and possible future climate conditions. We show that the heterogeneity in the flow domain is a key factor controlling seepage rates, since it causes channelized flow and local ponding in the unsaturated flow field.

1 Introduction

Recent interest in the construction of an underground nuclear waste repository has stimulated detailed investigations in the thick tuff formations at Yucca Mountain, Nevada, which are located approximately 200 meters above the water table in unsaturated fractured rock. Crucial for the performance of any underground waste repository is the amount of water seeping into the waste emplacement drifts. Overall, this seepage rate is limited by the percolation flux arriving at the repository horizon. At the present state, percolation flux in the unsaturated zone at Yucca Mountain is assumed to be fairly small due to the low precipitation; current estimates for the average gravity driven flux range from about 1 mm/yr up to about 20 mm/yr (Bodvarsson et al.[1]). The fluxes, however, could become as high as several hundred millimeter per year in the future because of long-term climate changes. Therefore, potential seepage rates at Yucca Mountain may be large enough to significantly affect the waste canister environment.

The long-term situation in the drifts several thousand years after waste emplacement will be characterized by a relative humidity level close or equal to 100%, as the drifts will be sealed and not ventilated, and the waste packages have cooled. Seepage into these drifts will only be possible if the hydraulic pressure in the rock close to the drift walls increases to positive values; i.e., the flow field becomes locally saturated. Different factors can give rise to such an increase, e.g., (1) the flow disturbance by the drift geometry, giving rise to a pressure increase above the crown, and/or (2) the effect of heterogeneity, in particular local permeability contrasts, promoting "channelized" flow with locally "ponded" conditions. In the present paper, we have developed and applied a methodology to estimate the potential rate of seepage into underground openings as a function of percolation flux, rock properties, and degree of heterogeneity. Our approach conceptualizes the fractured rock in the drift vicinity as a stochastic continuum with significant variation in permeability. A 3-D numerical model is used to simulate the heterogeneous steady-state flow field around the drift, with the drift geometry explicitly represented within the numerical discretization grid.

2 Conceptual Model

The hydrogeological parameters used in our study are chosen as representative for the Topopah Spring Welded Tuff (TSw), a formation at Yucca Mountain in which the potential waste repository is assumed to reside. The rock in this formation is intensely fractured, with the fracture permeability being several orders of magnitude higher than the matrix permeability. In fact, the saturated conductivity of the matrix is so small that, without the presence of fractures, gravity-driven flux would be limited to less than 1 mm/yr. As a result, the percolation flux through the TSw-unit occurs predominantly in the fractures, and the probability of seepage into drifts is mainly related to the fracture flow field. It was concluded from both fracture mapping and numerous *in-situ* interference air injection test data that the TSw-formation comprises a well-connected fracture network which, on a scale much smaller than the drift radius, behaves equivalently to a continuous, yet heterogeneous medium with strong variation in permeability (Tsang & Cook[5]). We therefore analyze the seepage problem using a stochastic fracture continuum model that accounts for the spatial variation of fracture permeability in the formation. In the absence of reliable information on the random structure of the characteristic function fitting parameters (van Genuchten[6]), we assume uniform values for fracture air entry pressure, $1/\alpha$, and pore size distribution coefficient, n. The rock matrix is neglected, since matrix flow would only become important for transient events such as short-term percolation pulses. However, the present conceptual model of the unsaturated zone at Yucca Mountain assumes that the major fraction of water infiltrating from the surface is dampened in the non-welded Paintbrush formation located above the repository level, so that an approximately steady-state percolation flux can be considered for the underlying units (Bodvarsson et al.[1]). Thus, we can limit our study to steady-state scenarios using a single continuum stochastic model of the fracture flow.

The data used for the generation of the heterogeneous fracture permeability fields are mainly based on the analysis of *in-situ* air injection tests (Tsang & Cook[5]) and fracture surveys (Bodvarsson et al.[1]). Three realizations of random fracture permeability fields with 50x35x43 m side length were generated on a cluster of 200x140x172 cubic elements to represent the rock mass in the drift vicinity. The random field generation was performed with the non-parametric, multiple indicator simulator SISIM of the geostatistical library GSLIB (Deutsch & Journel[2]). In the so-called base case property set, which represents the current "best" estimates derived from site characterization efforts, the geometric mean of the fracture permeability distribution, k_g, is 10^{-13} m^2, with a standard deviation, $\sigma_{\ln k}$, of 2.1. A spherical correlation structure with a correlation parameter of 2 m is adopted for the bulk of permeability values, while the high end of the permeability distribution is assigned a larger vertical correlation of 14 m to account for the presence of large, widely spaced fractures. The characteristic properties for the van Genuchten[6] relationships are $1/\alpha = 10^3$ Pa and $n = 2.7$. In addition to these base case properties, we studied parameter sensitivity by varying k_g and $1/\alpha$.

3 Simulation Methodology and Results

The unsaturated steady-state flow problem in the fracture continuum is solved under the assumption of isothermal conditions and a passive gas phase (Richards' equation). The simulations are performed with the multi-component, multi-phase simulator TOUGH2 (Pruess[4]). The model domain is 15 m wide, 16.5 m deep and 20.0 m high, with the drift being represented by a horizontal open cylinder of 2.5 m radius, placed in the center of the lower part of the domain (Figure 1). The simulation runs are performed on a rectangular mesh with cubic grid blocks of 0.25 m side length. The circular shape of the drift is approximated by eliminating the inner blocks whose centers are within a radius of 2.5 m. We checked the accuracy of the discretization by comparing simulation results with the analytical solution of Philip et al.[3], and found good agreement.

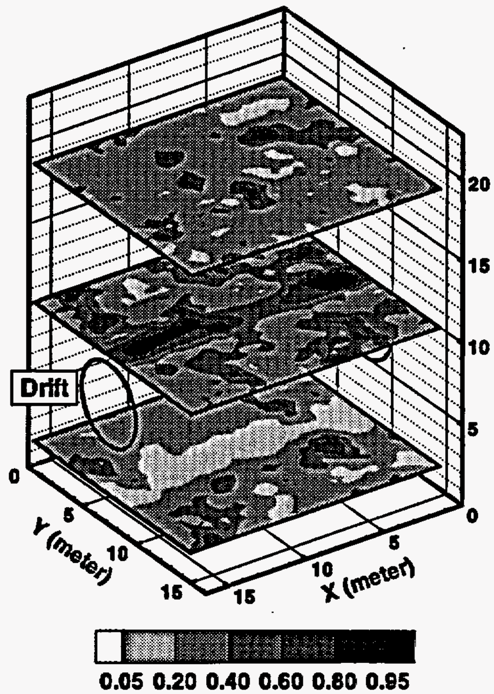

Figure 1: Saturation contours for a percolation flux of 200 mm/yr

The simulation scenarios studied comprise percolation fluxes ranging from 5 to 1000 mm/yr; the lower limit represents the average present-day percolation flux at the repository level, the upper limit represents maximum flux values estimated for an extreme future climate scenario. The percolation flux arriving at the drift model domain is represented by a constant inflow rate imposed at the top boundary. The four sides of the model domain are no-flow boundaries, and the bottom boundary has a free drainage condition. The drift wall boundary is modeled as a zero capillary pressure condition, representing a relative humidity of 100% in the drift.

3.1 3-D Unsaturated Flow in the Drift Vicinity

Figure 1 shows a typical flow field in the vicinity of the drift, presenting saturation contours in three horizontal slices of the model domain for a future climate scenario of 200 mm/yr percolation flux. The property set used represents the base case conditions as described earlier. In the horizontal plane just above the drift (middle horizontal slide), liquid accumulates at the drift crown as the vertical gravity-driven flow is diverted around it, while in the horizontal plane below the drift a low-saturation shadow develops. In addition to this flow perturbation effect, the saturation contours reflect the heterogeneity of the model area, showing several locations where "channelized" flow accumulates creating high saturation values dependent on local permeability contrasts. In fact, at some of these locations, the saturation reaches unity, representing a local ponding condition. Obviously, the probability that local ponding occurs is highest near the stagnation point at the drift crown. Eventually, seepage into the drift occurs when a local ponding condition is encountered in a grid element adjacent to the drift wall.

3.2 Total Seepage into the Drifts

Various flow scenarios have been simulated for the base case property set with percolation fluxes ranging from 5 to 1000 mm/yr. Figure 2 summarizes the results of these simulation runs for the three realizations considered; it gives the total seepage flux into the drift as a function of the inflow at the top boundary of the model. The seepage flux is expressed as a percentage of the percolation flux over an area corresponding to the vertical shadow of the drift. As shown in Figure 2, seepage into drifts at Yucca Mountain is likely to start when steady-state percolation fluxes are tens of millimeters per year, the rate of seepage being strongly dependent on the assumed percolation scenario. Thus for future climate conditions with higher infiltration than the present state, drifts at Yucca Mountain will be

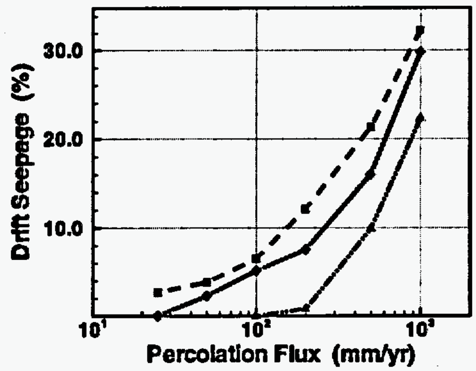

Figure 2: Relative seepage rate for three realizations of random fields.

vulnerable for water to enter. In comparison to results obtained for a homogeneous flow domain, the seepage threshold fluxes are about an order of magnitude smaller, indicating the important effect of local saturation variations (local ponding) as a result of the heterogeneity.

The relative seepage rates increase steadily from small percentages at lower percolation rates to about 30% at 1000 mm/yr. This means that even for the high percolation scenario, about 70% of the flux can be diverted around the capillary barrier formed by the drift. The general trend of increasing seepage with percolation flux is similar for all three realizations considered in our study. At higher percolation rates, the variability of the relative seepage rate is reasonably small, as the summation of the seepage fluxes at different locations along the length of the drift walls acts as an averaging filter. For smaller percolation fluxes, however, we obtain significant variation between the three realizations, despite the fact that the random fields are very similar. We may expect that the seepage locations along the drift wall are sparsely distributed for small percolation fluxes, so that in these cases, the size of the model domain may not be large enough to provide a meaningful averaging. This points to the need for a stochastic approach to estimate the probability, distribution and rate of seepage into drifts, considering that numerical modeling of small-scale heterogeneities in very large 3-D domains is a challenging task.

3.3 Sensitivities

Our sensitivity study includes simulation scenarios using different flow properties, changes in the drift geometry, different random structures of the permeability fields, and alternative drift wall boundary conditions. In this paper, we shall only present the sensitivity to two key parameters of the unsaturated flow, i.e., the geometric mean of the fracture permeability fields, k_g, and the fracture air entry pressure, represented by the van Genuchten parameter, $1/\alpha$. Note that changes in mean fracture permeability do not affect the random field structure; the permeability distribution is only shifted to smaller or larger values. A total number of four different k_g-values and five different $1/\alpha$-values was considered, forming a matrix of 20 different simulation runs for each percolation scenario.

Figure 3 gives an example of the results derived from the sensitivity study, showing the relative amount of seepage plotted over the parameter values for a percolation flux of 200 mm/yr. Seepage is obtained for 12

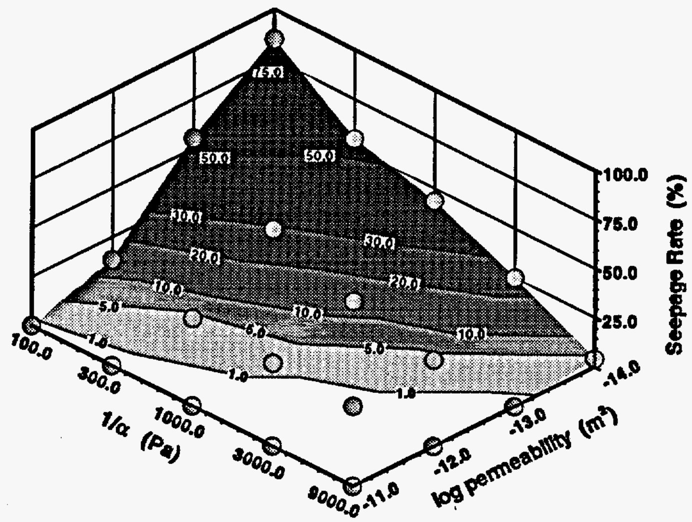

Figure 3: Relative seepage rate for different parameter combinations

out of 20 cases, namely those cases where both k_g and $1/\alpha$ are small. Qualitatively similar results were obtained for all other percolation scenarios. Thus, at a given percolation flux, seepage is most likely to occur for fractured formations with a small capillarity (small $1/\alpha$) and a small mean permeability. The latter point is somewhat counter-intuitive, as one might expect seepage to be most likely in high-permeable fractured rock. However, due to the nature of unsaturated flow with the drift acting as a capillary barrier, seepage is most probable in low-permeable regions: The smaller the permeability value at a given percolation flux, the more saturated becomes the rock, and the more likely is local ponding at the drift walls.

4 Conclusions

We have developed and applied a methodology to study the potential rate of seepage into underground cavities embedded in a unsaturated, heterogeneous fractured rock formation. The problem studied was chosen as representative of the conditions at the potential underground waste repository at Yucca Mountain, where nuclear waste is supposed to be stored in numerous underground emplacements drifts. For Yucca Mountain, the heterogeneity in the flow domain appears to be the most important factor for seepage to occur, because it promotes "channelized" flow and local ponding conditions. A homogeneous model of the fractured rock around the drifts can severely underpredict the seepage rate. Sensitivities derived from numerical and theoretical considerations indicate that, in addition to the assumed percolation scenario, the potential rate of seepage is strongly affected by the mean fracture permeability, the capillarity of the fractures, the degree of heterogeneity, the drift size and shape, and the assumed drift wall boundary condition. The studies presented are intended to be exploratory, with Yucca Mountain used as an example. We believe that the conceptual framework developed here can be useful for a variety of other hydrogeologic and engineering applications.

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